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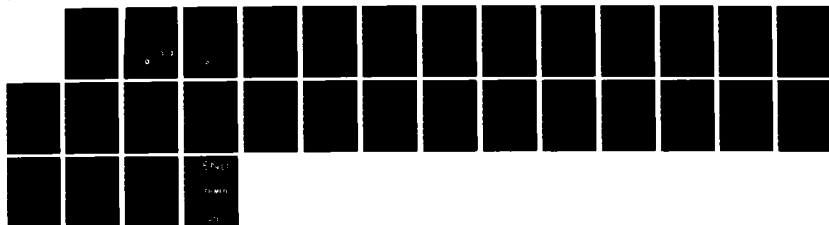
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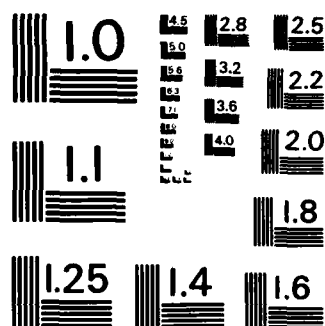
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### ULTMAT

A PROGRAM FOR PREDICTING  
THE ULTIMATE STRENGTH  
OF SHIP CROSS SECTIONS

Neil G. Pegg - Peter Cox

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## ULTMAT

### A PROGRAM FOR PREDICTING THE ULTIMATE STRENGTH OF SHIP CROSS SECTIONS

Neil G. Pegg - Peter Cox

October 1985

Approved by L. J. Leggat

H/Hydrodynamics Sections

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### Abstract

The theory and use of the computer program 'ULTMAT' is discussed in this report. It is the result of an initial investigation into ultimate strength analysis and is intended to serve as a basis for further development in this area. The program incorporates the theory of Faulkner for ultimate strength estimation. Given the geometric properties of a ship cross section, the program works interactively to predict the maximum load which the section can withstand before catastrophic collapse. In this manner, it provides an estimation of the reserve strength of a structure when taken beyond its linear elastic limit.

### Résumé

Le présent rapport porte sur la théorie et l'utilisation du programme informatique "ULTMAT" qui est le résultat d'une première recherche sur l'analyse des contraintes de rupture et qui est destiné à servir de base pour les prochains travaux dans le domaine. Le programme utilise la théorie de Faulkner pour estimer les contraintes de rupture. Comte tenu de la géométrie de la section d'un navire, il procède interactivement pour prévoir la charge maximale que la section peut supporter avant de céder totalement. De cette façon, il donne une estimation de la résistance résiduelle d'une structure qui est sollicitée au-delà de sa limite d'élasticité linéaire.

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## NOTATION

|                  |   |
|------------------|---|
| $a$              | length of stiffener   |
| $A_{be}$         | area of combined plate and stiffener prior to failure                                 |
| $A_s$            | area of stiffener   |
| $b$              | plate width   |
| $b_e$            | effective plate width prior to failure  |
| $b'_e$           | reduced effective plate width at failure  |
| $E$              | Young's modulus of material   |
| $E_T$            | tangent modulus of material   |
| $I_{x_{be}}$     | moment of inertia of combined plate and stiffener at failure                          |
| $\rho$           | ratio of stress at beginning of inelastic behaviour to the yieldstress in compression |
| $R$              | welding strength reduction factor   |
| $r_c$            | radius of gyration  |
| $t$              | plate thickness   |
| $\lambda_c$      | Euler column slenderness ratio  |
| $\beta$          | width to thickness ratio of plate   |
| $\sigma_y$       | yield stress of material  |
| $\sigma_f$       | failure stress of material  |
| $\phi$           | strength reduction factor   |
| $\epsilon_{avg}$ | average strain in material  |
| $\epsilon_y$     | yield strain of material  |

## 1. INTRODUCTION

This report describes the computer program, ULTMAT, a structural analysis tool using ultimate strength theory for the preliminary analysis of the strength of ship cross sections. Given the cross section geometry and material properties, the program determines the maximum applied moment which the section will resist before catastrophic failure due to structural collapse occurs. This enables the analyst to quickly evaluate the integrity of a design by comparing this collapse moment to a specified elastic design moment.

The ship cross section, as referred to in this work, consists of all plating and longitudinal stiffeners which are effective in supporting longitudinal stress in the ship hull. These comprise the decks, sides and bottom of the ship which are in the form of grillages; ie. orthogonally stiffened plate sections (Figure 1).

The program uses the well accepted assumption that the ship as a whole behaves as a beam undergoing either a 'hogging' load which results in tension in the top deck and compression in the bottom, or a 'sagging' load which results in the opposite stress pattern. The assumption of linear strain through the cross section is maintained, but due to the onset of inelastic behaviour well before collapse, a nonlinear stress pattern results (Figure 2).

The method of ultimate strength analysis uses nonlinear post buckling theory to predict the ultimate bending moment that the structure can withstand. Stated simply, it determines the load at which a critical structural component will fail through yielding or buckling of its associated members. The additional assumption is made that the members are designed against buckling elastically.

The prediction of the occurrence of buckling and post buckling, nonlinear behaviour is a very complex field and is by no means well understood. Several methods have been proposed based on a combination of plastic theory and experimental work. The method chosen for ULTMAT is based on the work of Faulkner<sup>1</sup>. It determines the ultimate strength for a 'hogging' or 'sagging' vertical load or a similar transverse load, and takes into account the effects of residual stresses from welding. It does not take into account the effects of local lateral loads, lateral torsional buckling (tripping) of the stiffeners or the effects of curved geometry in the ship cross section. These factors could be significant for some cross sections, and methods of dealing with them are currently under investigation.<sup>2,3,4,5,6,7,8</sup>

## 2. THEORY

The ship structure is made up of three main components; 1) plates as the primary structure, 2) panels consisting of plates with stiffeners in one direction, and 3) grillages consisting of several panels and both longitudinal and transverse stiffeners. Localized failure of plating through yield or buckling is not considered catastrophic, whereas failure of panels or grillages is. Figure 3 illustrates the modes of failure for plates, panels and grillages.



The characteristic sometimes referred to as 'load shedding' causes a redistribution of load from failed structural components to other components. In a well designed, uniformly stiff structure, the failure of one panel would cause a domino effect by shedding its load to adjacent panels of similar construction, resulting in failure of an entire grillage. Thus, panel failure is the criterion for catastrophic collapse used in this program.

Panels can maintain their structural integrity after failure of the plating through the behaviour referred to as 'load shortening' <sup>1,9</sup> in the plates. After initial yielding or buckling, the plating is still able to carry a portion of the axial load which caused its failure. This post failure strength is shown in the load shortening curves of Figure 4 which are stress-strain diagrams for axially loaded plates with varying initial distortion. The portion of the load which the plate can no longer carry is transferred to the panel stiffeners. Panel failure occurs when the combined plate and stiffener section yields or buckles.

In representing a plate and stiffener combination, the plate is added to the stiffener in the form of an additional top flange. The thickness of this flange is the thickness of the plate, however the width of plating which acts effectively with the stiffener is not usually the full width of plating. This is due to certain nonlinear behaviour patterns in the plate stress. Buckling of the plate occurs at a low load level due to initial imperfections. This results in a stress differential across the plate with higher stress at the stiffeners and lower stress at the plate center (Figure 5). This reduction in effectiveness of the plate is represented by an effective plate width,  $b_e$ ;<sup>1</sup>

$$\frac{b_e}{R \cdot b} = \frac{2}{\beta} - \frac{1}{\beta^2} \quad (1)$$

where R is a welding strength reduction factor.  $\beta$  represents the width to thickness ratio of the plating including material property effects;

$$\beta = \frac{b}{t} \frac{\sigma_y}{E}$$

$b$  = stiffener spacing  
 $t$  = plate thickness  
 $\sigma_y$  = yield stress  
 $E$  = Young's modulus

At failure, a further reduction in the effectiveness of the plating contribution to stiffness of the combined section occurs. This reduction is dependent on the stress in the section at failure and is referred to as a reduced effective width,  $b'_e$ ;<sup>1</sup>

$$\frac{b'_e}{R \cdot b} = \frac{1}{\beta} \frac{\sigma_y}{\sigma_f} \quad (3)$$

The stress at failure,  $\sigma_f$ , is related to the critical plastic Euler buckling stress of the combined plate and stiffener section at failure by;<sup>1</sup>

$$\frac{\sigma_f}{\sigma_y} = 1 - p(1-p) \lambda_c^2 \quad 0 \leq \lambda_c \leq 1/\sqrt{p} \quad (4)$$

where  $p$  is the ratio of plate stress at the beginning of inelastic behaviour to the yield stress and  $\lambda_c$  is the Euler column slenderness ratio for the panel;

$$\lambda_c = \frac{a}{\pi r_c} \sqrt{\frac{\sigma_y}{E}} \quad (5)$$

where  $a$  = length of stiffener, and  $r_c$  is the radius of gyration of the combined plate and stiffener at failure;

$$r_c = \sqrt{\frac{I_{x_{b'_e}}}{A_{b_e}}} \quad (6)$$

where;

$I_{x_{b'_e}}$  = moment of inertia of the combined plate and stiffener at failure using  $b'_e$  for the plate width, and

$A_{b_e}$  = area of the combined plate and stiffener just prior to failure using  $b_e$  for the plate width

An iterative solution process is required to arrive at the failure stress  $\sigma_f$  (equation 4), of the panel as  $\sigma_f$  is dependent on the reduced effective width  $b'_e$  (equation 3), which in turn is dependent on  $\sigma_f$ .

The preceeding information gives the stress at which the panel fails,  $\sigma_f$ . The effective area of the combined stiffener plate section just prior to failure is given by;

$$A_{b_e} = b_e t + A_s \quad (7)$$

where  $A_s$  = stiffener area and  
 $t$  = plate thickness.

Welding produces residual stresses in the plating and stiffener which also can significantly contribute to the reduction in the plating effectiveness. A block of relatively large tension stress, as high as  $\sigma_y^1$  can exist in the plate at the stiffener connection. This causes an equal compression stress in the plate midway between the stiffeners and a reduction in the load carrying capacity of the plate. This effect is accounted for by applying an additional reduction factor to the effective widths:<sup>1</sup>

$$R = 1 - \frac{2n}{(b/t - 2n)} \frac{\beta}{(2\beta - 1)} \frac{E_T}{E} \quad (8)$$

for  $\beta \geq 1$

where  $\beta$  is defined in equation 2,

$n$  = a factor dependent on welding type and shakedown effects,  $3.0 \leq n \leq 4.5$  for most naval ships,  $n=3.75$  in this program, and

$E_T$  = the tangent modulus of the plate material defined by;

$$\begin{aligned} \frac{E_T}{E} &= \frac{3.62\beta^2}{13.1 + \frac{1}{4}\beta^4} && \text{for } 0 \leq \beta \leq 1.9/\sqrt{\rho} \\ &= 1 && \text{for } \beta \geq 1.9/\sqrt{\rho} \end{aligned} \quad (9)$$

The reduction factor  $R$  is then applied to  $b_e$  and  $b'_e$  in equations 1 and 3 to be used in the calculation of effective plate area and failure stress by equations 4 through 7.

The reduction in the effective plating area due to buckling and welding effects and the reduced failure stress are incorporated into the ship cross section by applying a strength reduction factor to various portions of the ship cross section which are under a compressive load. This reduction factor is defined as;<sup>1</sup>

$$\phi = \frac{\sigma_f}{\sigma_y} \frac{A_S + b_e t}{A_S + bt}$$

The ship cross section is divided into regions of similar structural configuration (i.e., main deck, side panels, bottom, interior decks, longitudinal bulkheads) and strength reduction factors are determined for each region. The cross section is then placed into a state of fully plastic bending (either hogging or sagging) where the reduced areas in compression and the full areas in tension are at the material yield stress. An iteration is then performed to locate the neutral axis and bring moment equilibrium to the section. The resulting plastic moment on the section is the maximum moment which that section can withstand before catastrophic collapse.

The computer program ULTMAT, utilizes the method of Faulkner<sup>1</sup> described above to give the maximum moment (ultimate load) for various cross sections of the ship. A digitized cross section file is required to run the program. With a good digitizing program and ULTMAT, a designer can quickly establish the strength characteristics of various cross section designs.

### 3. PROGRAM USE

The equipment necessary to use this program is a terminal with graphics and cursor capability, a computer with a Tektronix PLOT10 library (this program was developed on a VAX 11/750), and a facility for digitizing ship cross sections. The cross sections, made up of plates and beams defined geometrically by node locations, were digitized for this study using a digitizing tablet and the program TPGEOM<sup>11</sup>.

As a test, cross sections of a DDH 280, Tribal class destroyer were analyzed with ULTMAT. Examples of the cross sections and regions of strength are shown in Figures 6, 7 and 8 as well as in Appendix A. Results from the two cross sections of the DDH 280 in Figure 6 and Appendix A showed an ultimate moment of  $4.45 \times 10^9$  in-lbs for bulkhead 8 compared with an elastic moment of  $2.88 \times 10^9$  in-lbs, and an ultimate moment of  $6.43 \times 10^9$  in-lbs for frame 35 compared with an elastic moment of  $5.56 \times 10^9$  in-lbs. The elastic moments were calculated with the program SCRAP<sup>10</sup>. This indicates considerable reserve strength in bulkhead 8 but very little in frame 35. An investigation into the buckling characteristics of frame 35 would be warranted here.

After displaying the digitized cross section on the terminal screen, the graphics cursor is used to define the lower left and upper right corners of the regions of strength. A strength reduction factor is then calculated and presented for each region. Checks are made to assure that a node is not defined in more than one region. Once the entire cross section has been defined, which the user must insure, an iteration proceeds to locate the neutral axis and calculate the ultimate moment. Regions which are omitted are automatically assigned a strength reduction factor of 0.9 which will be overly conservative for some sections but is appropriate for corners and connections which may be easily missed. An example run of this program is given in Appendix A.

#### 4. CONCLUDING REMARKS

The computer program ULTMAT was intended to serve as an initial investigation into ultimate strength methods and to provide a base for further development. Unfortunately, due to the destructive nature of bringing structures to their ultimate strength limits, experimental verification of the program results is unlikely at this time.

In future versions of the program, in addition to investigating the effects of the factors discussed in the theory section, several other factors of concern in estimating the strength of the ship will be considered. These include the determination of what decks and stiffeners to consider in the cross section for the strength calculation. Some decks and beams only extend over a small length of the ship and may be relatively ineffective. Hatch openings and other obstructions interrupt the continuity of the structural system and their effects should be studied. The question of how the superstructure affects the beam behaviour of the ship hull is also a topic of current concern. Materials other than regular grade structural steel, which have a different nonlinear behaviour and thus a different post buckling description than currently addressed by the program may also be incorporated.

Adamchak<sup>2</sup>, has recently produced an ultimate strength program which produces a moment vs curvature diagram for the section in addition to the failure load. This feature will be incorporated in a future version of ULTMAT as it provides more insight into the failure mechanism of the structure. The approximate method discussed in this report could be further improved by using the finite element method in a step by step loading, including nonlinear post buckling behaviour. This would give a clear picture of the behaviour of all components in the section, but would of course be much more expensive.

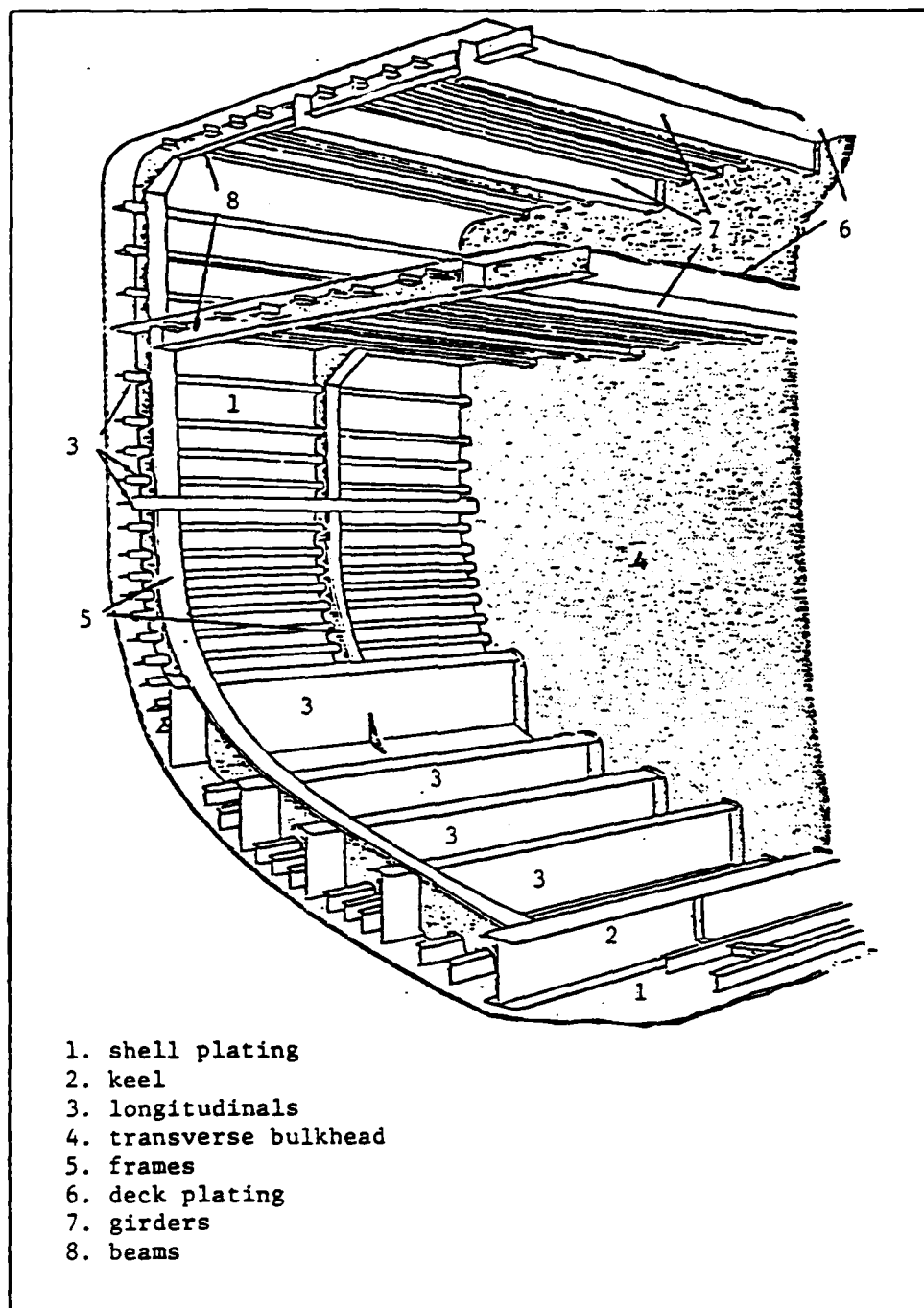


Figure 1. Typical midship section illustrating the common structural components

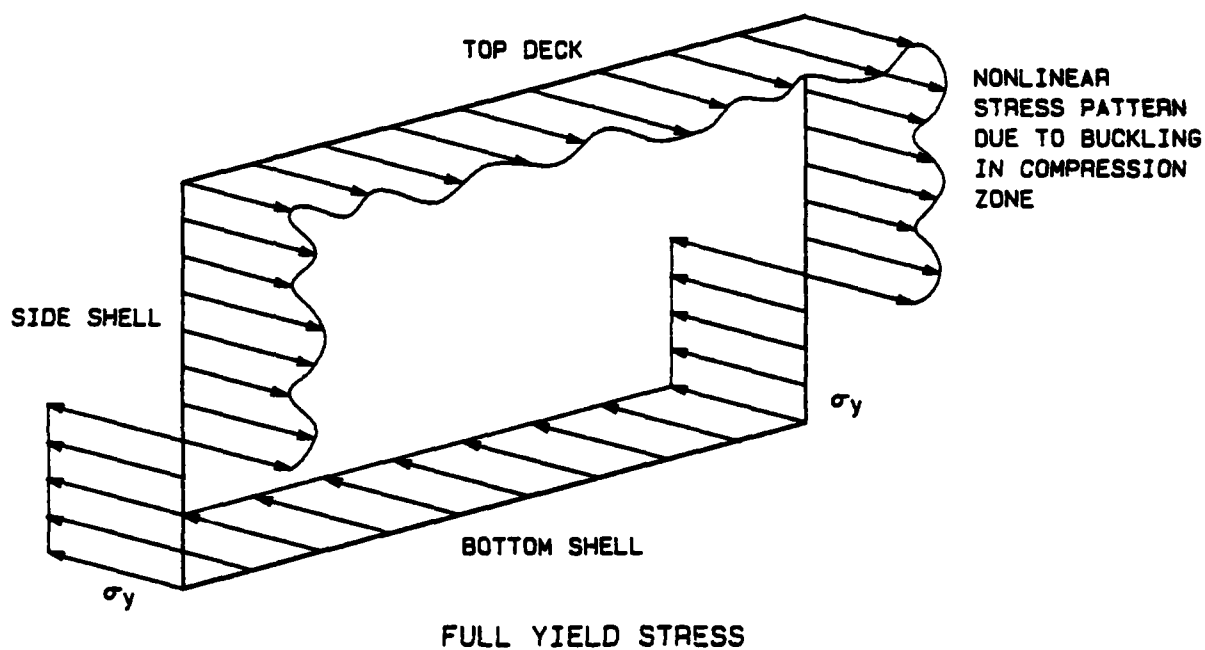


FIGURE 2. Stress distribution in ship cross section at ultimate load due to sagging

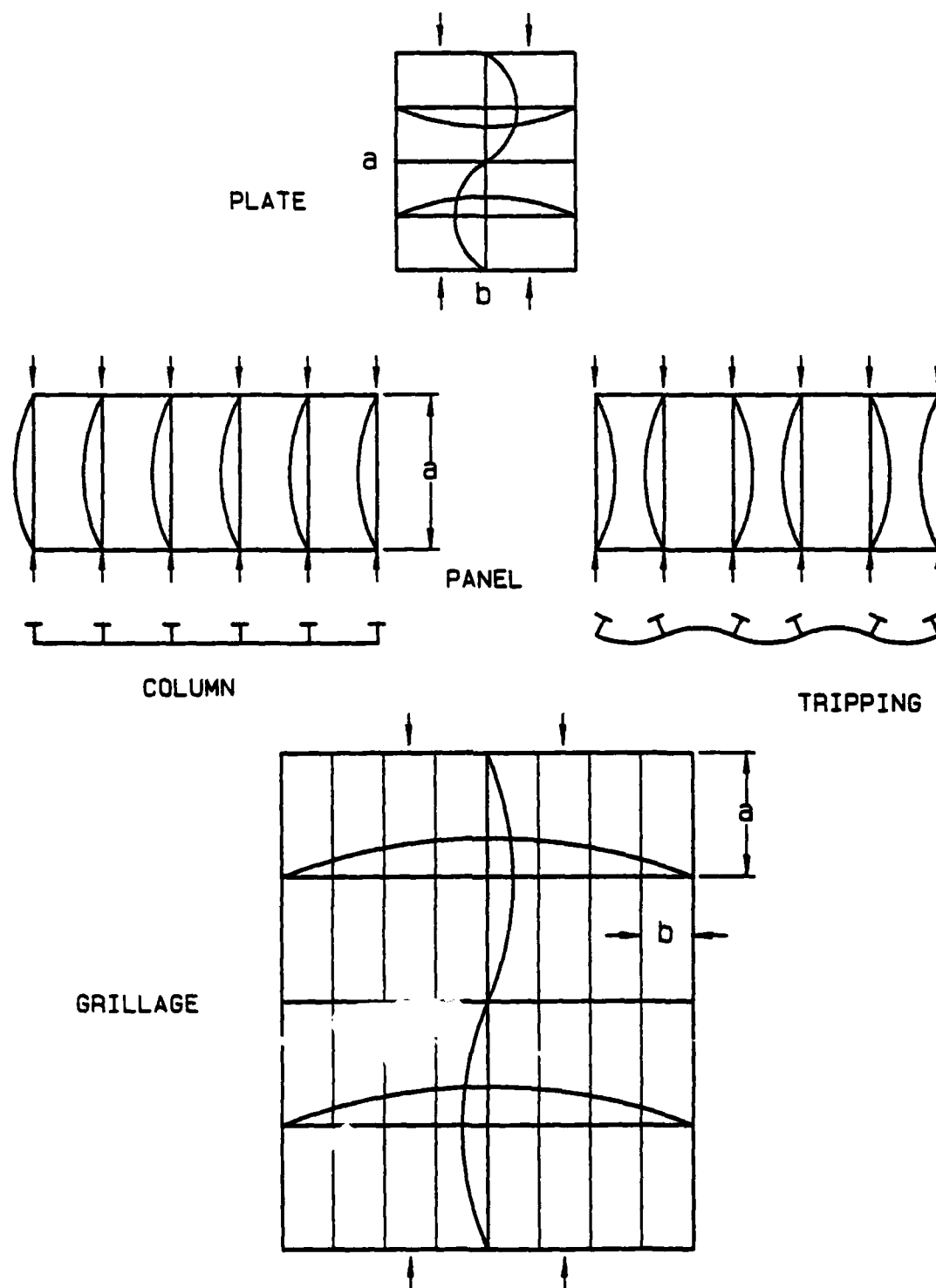
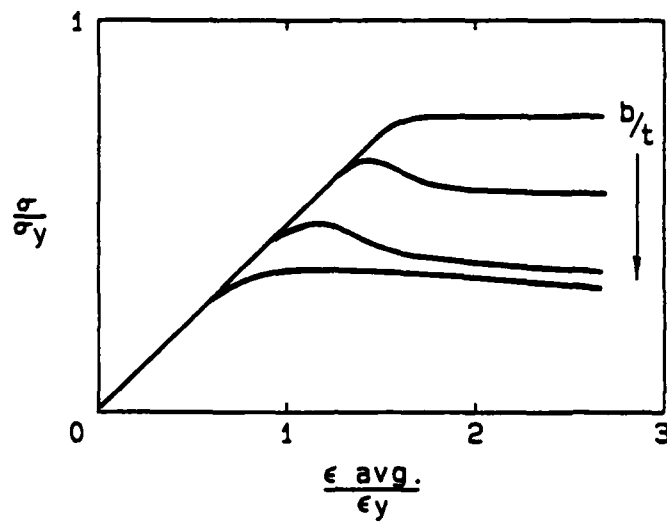
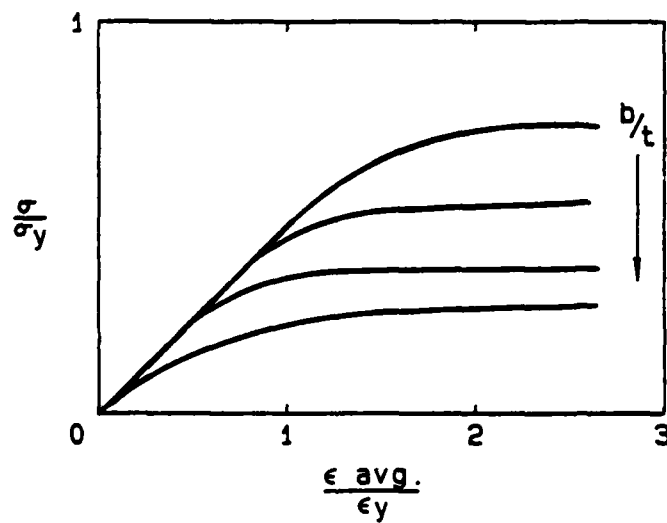


FIGURE 3. Modes of failure in the ship cross section





NEARLY PERFECT PLATES



IMPERFECT PLATES WITH RESIDUAL STRESS

FIGURE 4. Load shortening curves for square plates under axial compression

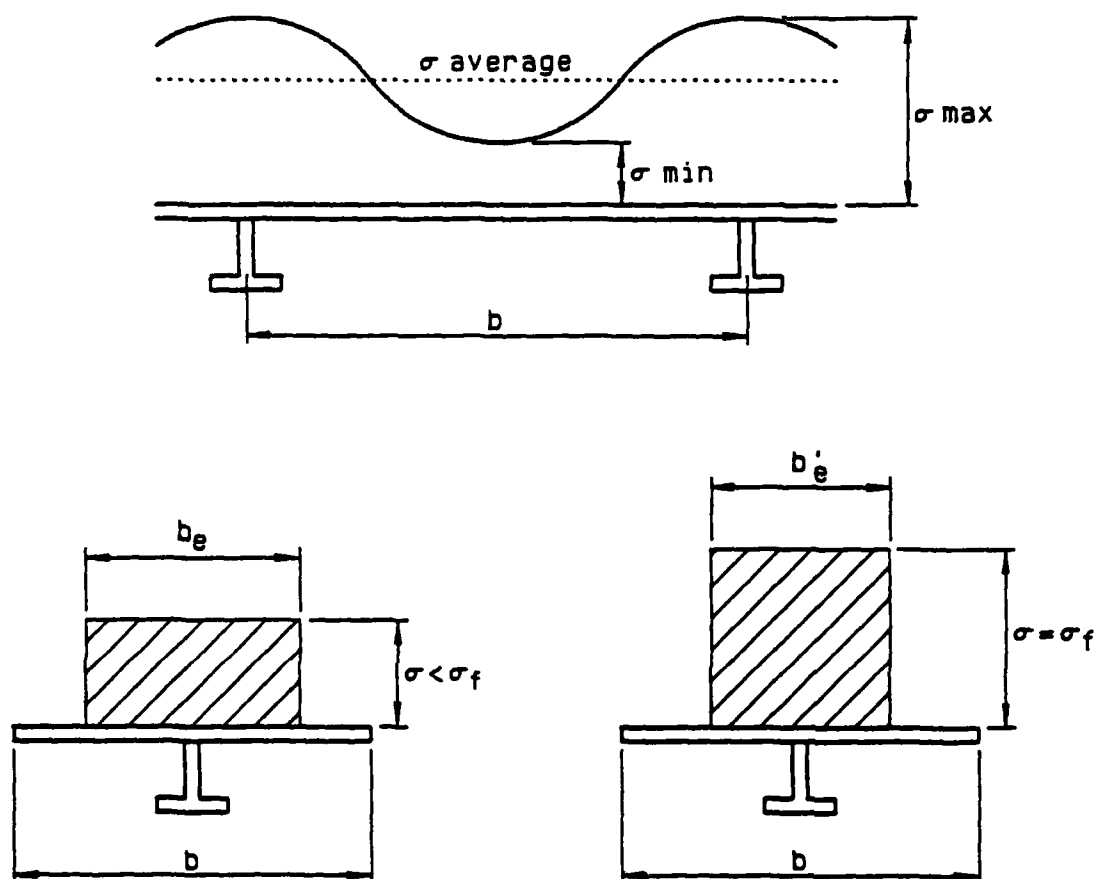


FIGURE 5. Stress distribution in plate between stiffeners and effective widths before and at failure

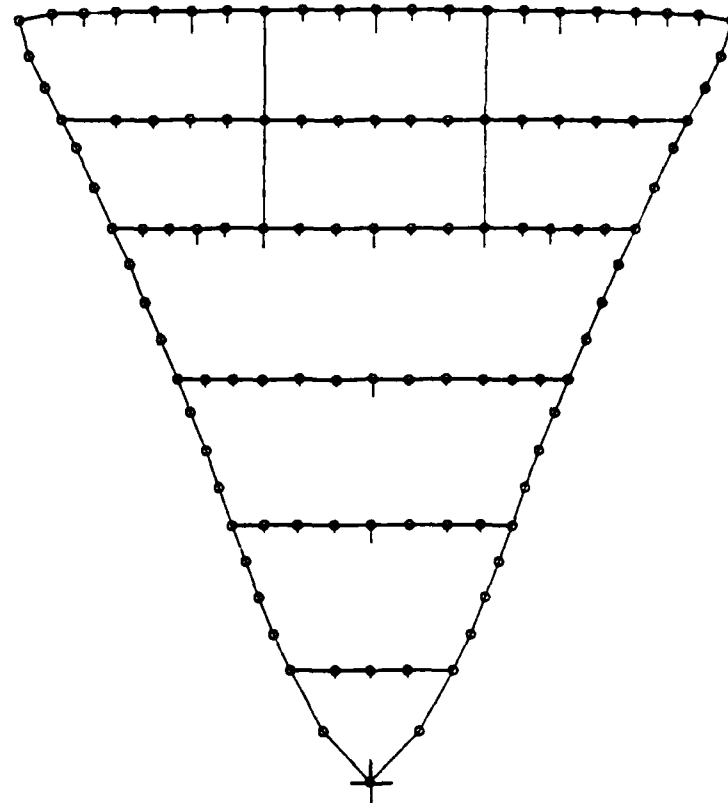


FIGURE 6. Digitized cross section of bulkhead 8 of DDH280

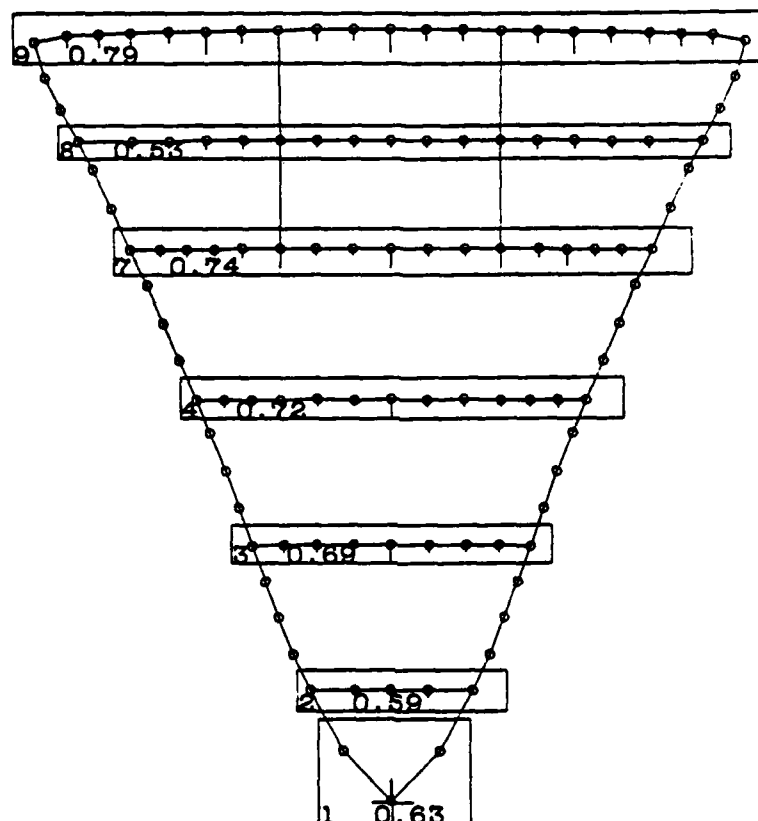


FIGURE 7. Figure 6 with regions of strength defined and load reduction factors calculated for decks

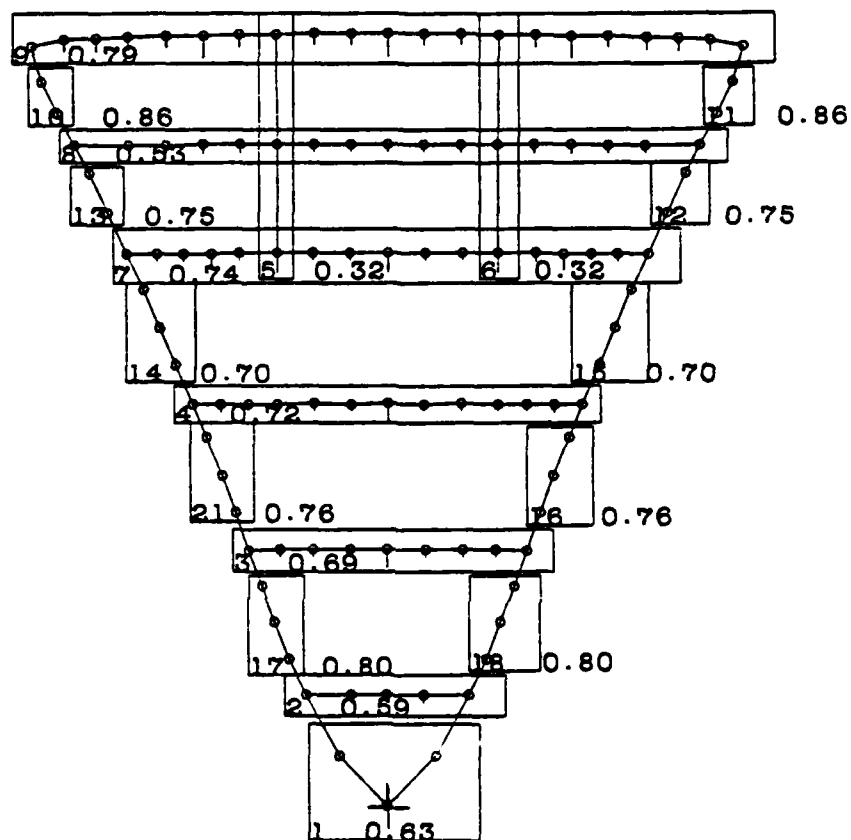


FIGURE 8. Figure 6 with regions of strength defined and load reduction factors calculated for entire cross section

APPENDIX A: Sample Run of Ultmat on Frame 35 of DDH280

@LOAD ULTMAT,PS:(LIB>PLOT10/LIB

@ST

ENTER TERMINAL LINE SPEED  
2400

WHAT TERMINAL IS BEING USED.

ENTER 0 FOR ADM  
ENTER 1 FOR 4010  
ENTER 2 FOR 4014  
ENTER 3 FOR 4113 COLOUR VIDEO  
0

DOES THIS TERMINAL HAVE CURSORS.(Y OR N)  
Y

IS EXTRA EQUIPMENT TO BE USED.

0-NO EXTRA EQUIPMENT  
1-FILE MANAGER  
2-4662 PLOTTER  
3-4663 PLOTTER  
0

THE FOLLOWING FILES ARE REQUIRED TO RUN THIS PROGRAM

SHPRFX.TMP - MATERIAL PROPERTIES  
SHPRFX.TTA - PLATE THICKNESS AND BAR AREAS  
SHPRFX.TBS - BEAM SECTION PROPERTIES  
TGPRFX.DAT - DIGITIZED SECTION FILE  
WHERE PRFX IS THE 4 CHARACTER PREFIX AND DAT  
IS THE 3 CHARACTER SECTION IDENTIFIER

ENTER THE FOUR CHARACTER FILE IDENTIFIER PREFIX EG.0280  
0280

ENTER SECTION ID NUMBER (EG.F35)  
F35

ENTER 1 FOR IMPERIAL UNITS E-30000000 PSI  
ENTER 2 FOR METRIC E-207000 MPA  
1

DO YOU WISH TO SEE NODE NUMBERS

ENTER 1 FOR YES  
ENTER 0 FOR NO  
0

THE TITLE OF THIS FILE IS :  
TRANSVERSE FRAME 35 SUBSTRUCTURE 76 AT 2-2484 (FILE TGO280.F35)

NGN-128

WHAT IS THE FRAME SPACING IN INs  
60

DO YOU WISH TO SEE LATERAL LOADING  
ENTER 1 FOR YES  
ENTER 2 FOR NO  
2

THE PLOT WILL NOW APPEAR ON THE SCREEN  
CHOOSE THE REGIONS OF STRENGTH WITH THE CURSOR  
BY PLACING IT IN THE LOWER LEFT AND UPPER RIGHT  
CORNERS OF THE REGIONS AND PRESSING P TO DEFINE  
THE CURSOR POSITION - S WILL STOP SELECTION AND  
COMPUTE AND PLOT THE NEUTRAL AXIS AND THE ULTIMATE  
MOMENTS.

PRESS 1 RETURN TO CONTINUE  
1

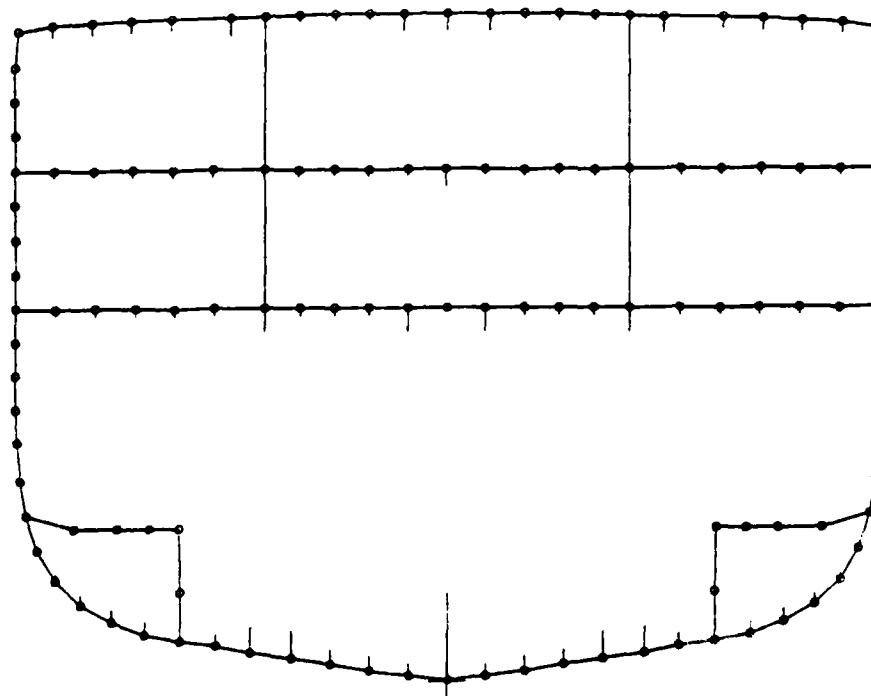


FIGURE A1. Digitized cross section of frame 35 of DDH280



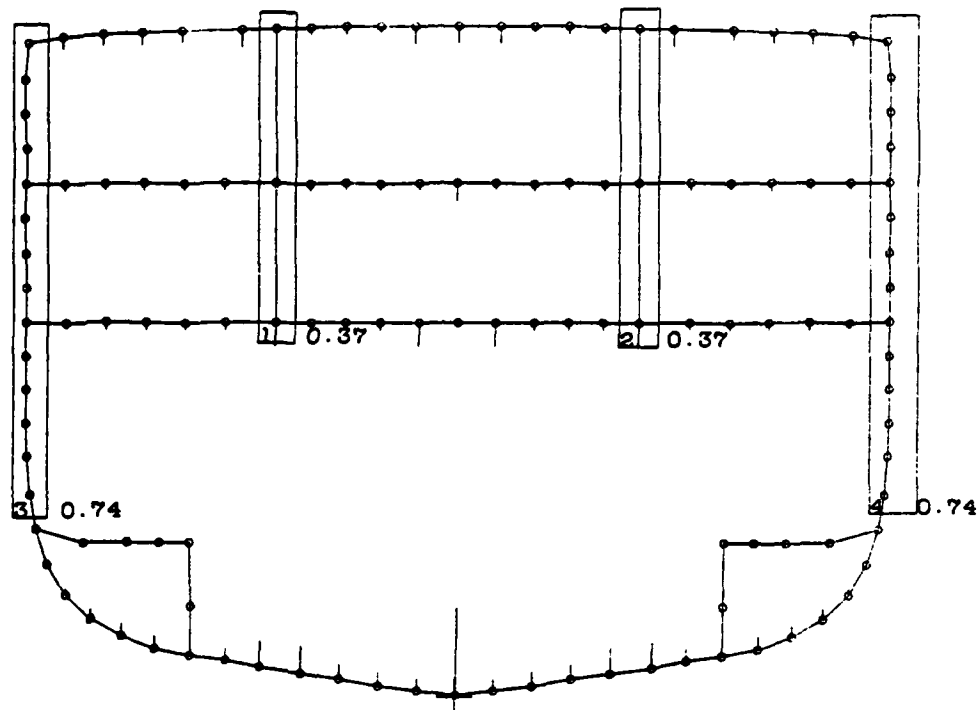


FIGURE A2. Figure A1 with some vertical components defined and strength reduction factors determined

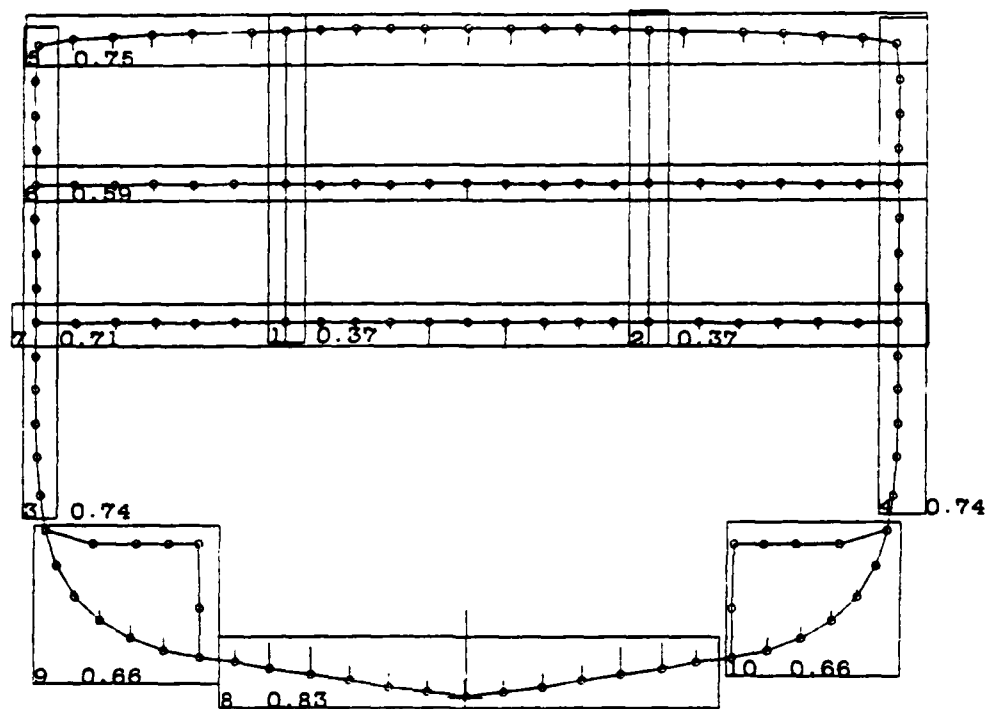


FIGURE A3. Figure A1 with all sections defined and strength reduction factors determined

SELECT THE REGIONS OF STRENGTH  
S STOPS SELECTION

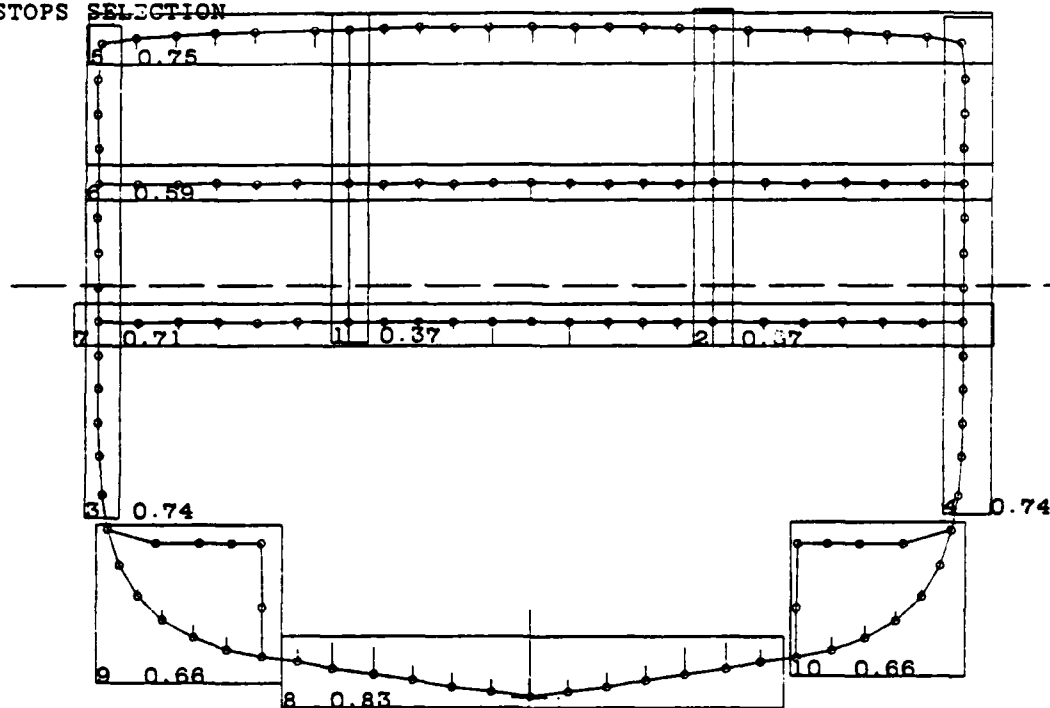


FIGURE A4. Pressing 'S' calculates and determines the position of the Plastic Neutral Axis - pressing 'RETURN' clears the screen and prints the results

THE AREA OF THE SECTION IS 1867.576 IN\*\*2

THE PLASTIC NEUTRAL AXIS IN SAGGING IS 257.7973 IN  
FROM THE KEEL

THE ULTIMATE SAGGING MOMENT IS 6.3230941E+09 LB-IN

THE PLASTIC NEUTRAL AXIS IN HOGGING IS 283.0356 IN  
FROM THE KEEL

THE ULTIMATE HOGGING MOMENT IS 6.3339983E+09 LB-IN

THE DATA FROM THIS RUN ARE ON FILE 0280F35.OUT

DO YOU WISH ANOTHER RUN, 0-NO,1-YES,2-RESTART

0

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